

Can the beta decay of neutral kaons be observed?

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Abstract

The rate of the beta decay of neutral kaons is calculated within the meson dominance approach taking into account the relation between the $KK\rho$ and $\pi\pi\rho$ coupling constants which follows from the vector meson dominance in electromagnetic interactions and isospin symmetry. The decay rate transforms into the following branching fraction summed over the charge states indicated: $B(K_L^0 \rightarrow K^\pm e^\mp \nu) = (2.53 \pm 0.10) \times 10^{-9}$. The error is dominated by our estimate of isospin violating effects. Experimental aspects of such a measurement are discussed.

PACS number(s): 13.20.Eb 12.40.Vv

In this work we built upon previous work by one of us [1] to give a prediction for the $K_L^0 \rightarrow K^\pm e^\mp \nu$ branching fraction which may be within the reach of some next generation neutral rare kaon decay experiments. The calculation presented here is performed using the meson dominance (MD) in weak interactions and the vector meson dominance (VMD) in electromagnetic interactions. Both these hypotheses naturally stem [1] from the Standard Model of electroweak interactions. The measurement of the $K_L^0 \rightarrow K^\pm e^\mp \nu$ decay can thus be considered as another test of the Standard Model.

The MD hypothesis leads [1] to the following formula for the $K^0 \rightarrow K^+ e^- \bar{\nu}_e$ and $\bar{K}^0 \rightarrow K^- e^+ \nu_e$ differential decay rate (see Fig. 1 for the corresponding Feynman diagram)

$$\frac{d\Gamma}{dt} = \frac{G_F^2 X_{K^0 K^+ \rho^-}}{3(4\pi m_{K^0})^3} \frac{t - m_e^2}{t^3} \sqrt{\lambda(t)} [\varphi_1(t) - \varphi_2(t)] \left(\frac{r}{r - t} \right)^2, \quad (1)$$

where t is the invariant mass squared of the outgoing lepton pair, r is the mass of the ρ meson squared, and

$$X_{K^0 K^+ \rho^-} = |V_{ud}|^2 \left(\frac{g_{K^0 K^+ \rho^-}}{g_\rho} \right)^2, \quad (2)$$

with g_s denoting the strong coupling constants. For the $g_{\pi\pi\rho}$ coupling constant, a simpler notation g_ρ is used. Furthermore,

$$\lambda(t) = t^2 + x^2 + y^2 - 2tx - 2ty - 2xy, \quad (3)$$

$$\begin{aligned} \varphi_1(t) = 2t^4 - (4x + 4y + z)t^3 + [2(x - y)^2 + z(2x + 2y - z)] t^2 \\ + 2z [(x - y)^2 + z(x + y)] t - 4z^2(x - y)^2, \end{aligned} \quad (4)$$

$$\varphi_2(t) = \frac{3tz}{r^2} (2r - t)(t - z)(x - y)^2. \quad (5)$$

Here, $x = m_{K^0}^2$, $y = m_{K^+}^2$, and $z = m_e^2$. The quantity (2) was estimated in Ref. [1] using the experimental rate of the $\tau^- \rightarrow K^- K^0 \nu_\tau$ decay. The value obtained, $X_{K^0 K^+ \rho^-} = 0.64 \pm 0.12$, led to the following branching fraction prediction $B(K_L^0 \rightarrow K^\pm e^\mp \nu) = (3.4 \pm 0.6) \times 10^{-9}$, where the sum over the charge states indicated is understood.

In more recent work [2] one of us has shown that the VMD hypothesis, together with the isospin invariance of the strong vertices and normalization conditions on the form factors, implies that the contribution of the ρ meson pole to the K^+ form factor is just half of that to the π^+ form factor. In terms of the coupling constants it means that

$$\frac{g_{K^+ K^+ \rho^0}}{g_\rho} = \frac{1}{2}. \quad (6)$$

To establish the connection of this result with our quantity (2) the isospin invariance relation $|g_{K^+ K^0 \rho^+}| = \sqrt{2} |g_{K^0 K^+ \rho^-}|$ is required. We thus obtain

$$X_{K^0 K^+ \rho^-} = \frac{1}{2} |V_{ud}|^2 = 0.4739 \pm 0.0008, \quad (7)$$

where the numerical value of $|V_{ud}|$ comes from Ref. [3].

Since the relative errors of all parameters that serve as input to our formula (1) are very small, it is important to discuss the systematic errors of our approach. They consist of several components.

First, we should account somehow for a possible violation of the isospin symmetry, which was assumed to be unbroken when deriving Eq. (7). Of course, there is no exact way to do that. Looking at the various quantities which reflect the violation of isospin invariance ($n - p$, $\pi^+ - \pi^0$, and $K^0 - K^+$ mass differences, $K^{*+} - K^{*0}$ width difference, violation of the $SU(2)$ relation between the K_{e3}^+ and K_{e3}^0 decay rates) we expect that the relative error connected with this phenomenon does not exceed four per cent, which we will take as our very conservative “educated guess”.

Second, the systematic error of the MD approach is almost certainly negligible in this case. We base our judgement on a very precise MD result [1] for the branching fraction of the $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ decay, which is a process analogous to that considered here. In both cases we are very close to the threshold, where the assumptions leading to the MD formulas are well satisfied [1].

Third, there are uncertainties in the form of the ρ meson propagator. One of us discussed this issue in Refs. [4,5], where references to some previous papers can also be found. Here, we proceed in the same way as in [5]. We calculate the integrated branching fraction twice, for two (extreme) choices of the ρ meson propagator and consider the difference between the two results as a measure of the systematic error. One of the choices is equivalent to using our original formulas (1-5) and the other to putting $\varphi_2(t)$, Eq. (5), to zero identically. Both choices lead to the same result¹, which after the conversion to units of inverse seconds reads:

$$\Gamma(K^0 \rightarrow K^+ e^- \bar{\nu}_e) \equiv \Gamma(\bar{K}^0 \rightarrow K^- e^+ \nu_e) = (4.887 \pm 0.008) \times 10^{-2} \text{ s}^{-1}. \quad (8)$$

The error quoted here reflects only the error of the V_{ud} element of the Cabibbo-Kobayashi-Maskawa matrix. So, the systematic error connected with the uncertainties in the ρ meson propagator is also negligible.

Using Eq. (8) and the experimental value of the K_L^0 lifetime [3] we arrive at the branching fraction

$$B(K_L^0 \rightarrow K^\pm e^\mp \nu) = (2.53 \pm 0.10) \times 10^{-9}. \quad (9)$$

The error is dominated by our “educated guess” of isospin violating effects.

For the other pseudoscalar mesons, beta decays (i.e. semileptonic transitions between the members of the same isotopic multiplets) may completely escape detection because of their extremely small branching fractions. The low-lying cases are discussed briefly below.

The branching fraction of the K_S^0 state, $B(K_S^0 \rightarrow K^\pm e^\mp \nu) = (4.37 \pm 0.17) \times 10^{-12}$, comes from Eq. (8) and the experimental value of the K_S^0 mean lifetime. The error is based on our guess above.

When calculating the decay rate of the $D^+ \rightarrow D^0 e^+ \nu_e$ decay, we can use the same formalism as we have applied to the beta decay of neutral kaons. The electromagnetic form

¹This can easily be understood because $\varphi_2(t)$ is proportional to $(m_e/m_\rho)^2$.

factors of the D^+ and D^0 mesons now contain, in addition to the ρ , ω , and ϕ terms, an important contribution from the J/ψ pole. But the J/ψ term transforms like an isoscalar and therefore again only the ρ meson pole contributes to the isovector part of the D^+ and D^0 form factors. And it is this condition, not the detailed structure of the isoscalar part, which leads, together with the normalization of the D^+ and D^0 electromagnetic form factors, to the relation between the strong coupling constants of the same kind as shown in Eq. (6). The value of $X_{D^+D^0\rho^+}$ is thus the same as that given in Eq. (7). The decay rate comes out about five times larger than that shown in Eq. (8), as a result of the larger mass difference and increased phase space. But the branching fraction is pushed to an unobservable value, $B(D^+ \rightarrow D^0 e^+ \nu_e) \approx 2.7 \times 10^{-13}$, by the very short D^+ lifetime.

In the (B^+, B^0) isomultiplet, the mass difference is smaller than the electron mass, so the beta transition is not possible.

Above we have discussed theoretical expectations for the branching fraction of the K_L^0 beta decay. Next we will briefly summarize some signatures of this decay and those accelerators and experiments which might have a chance to observe it.

First we note that the small $K^0 - K^+$ difference ($\delta m \approx 4$ MeV) gives striking characteristics² to the kaon beta decay events:

1. a charged kaon with momentum approximately that of the beam (the relative loss of momentum is less than $\delta m/m_{K^0}$) and very close to the initial direction of the beam ($\theta < \delta m/p_{K^0}$, where p_{K^0} is the beam momentum).
2. a large-angle electron (or positron) with small momentum ($p < (E_{K^0} + p_{K^0})\delta m/m_{K^0}$, where E_{K^0} is the beam energy).

Although these characteristics are striking, they are not simple to achieve. Many experiments are intentionally blind in the forward direction, where the kaon will be found. Not all experiments are in a position to measure the momentum of the incident kaon. And not all experiments have a magnetic spectrometer or other means to measure the momentum and angle of the charged decay products. Even for experiments with magnetic spectrometers and information on the incident kaon momentum and direction, the suppression of the $\pi^\pm e^\mp \nu$ modes, which are about 10^8 times more frequent than $K^\pm e^\mp \nu$, requires particle identification to discriminate between pions and kaons.

Because of the intense kaon beam requirement, there are only a few facilities in the world at which the kaon beta decay could be measured: Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (Fermilab), European Organization for Nuclear Research (CERN), Phi-factory DAΦNE at the Frascati National Laboratory, and the High Energy Accelerator Research Organization (KEK) in Tsukuba.

A natural place for the kaon beta decay measurement would be a beam designed for the important decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and similar rare decays of neutral kaons. Such beams are presently in place or in the planning or preparatory stages at all the laboratories mentioned above. The characteristics and advantages of the kaon beams and detectors vary:

²The formulas used below are valid if the beam momentum is much greater than δm , which is satisfied in the cases we consider.

(1) The completed experiment E871 at BNL was a search for the lepton family violating decay $K_L^0 \rightarrow \mu^\pm e^\mp$, with a limit set at the 4.7×10^{-12} level [6] and observation of the $K_L \rightarrow e^+e^-$ branching fraction as $(8.7^{+5.6}_{-4.1}) \times 10^{-12}$ [7]. This experiment had a double charged particle spectrometer with electron and muon identification. However, it was blind in the forward direction, and the kaon beta decay cannot be studied in their data [8].

(2) The KTeV experiment at Fermilab, [9]) has a beam of 70 GeV/c neutral kaon average momentum, leading to charged kaons of approximately 70 GeV/c momentum and nearly exactly straight forward (within about 0.06 mrad) and electrons up to about 1.1 GeV/c (the estimates here and below are given for the average beam momentum). The momentum kick of the spectrometer magnet (205 MeV/c) would allow the highest energy electrons to pass through, but would bend the kaons only by about 3 mrad, not enough to avoid the 50 mrad blind spot in the center of the calorimeter. The kaons might still be seen by the drift chambers, and some π/K rejection might be available from the transition radiation detectors, though they are optimized for e/π separation at lower energies. But these events would not be included in any data taken to date because of the trigger requirement of ≈ 20 GeV/c in the calorimeter. There is no time of flight and therefore no momentum information for the parent kaon.

(3) Experiment NA48 at CERN [10] has a kaon beam of 110 GeV/c, which, as for KTeV, would lead to charged kaons nearly straight ahead ($\theta < 0.04$ mrad). The latter thus remain in the beam pipe and cannot reach the detector. The electron momentum extends up to 1.8 GeV/c. Experiment NA48 has a magnetic spectrometer but no time of flight for the incident kaon, nor particle identification to distinguish charged kaons and pions.

(4) The KLOE detector at DAΦNE [11] is a general purpose detector with $K_S K_L$ pairs produced nearly at rest by decays from the $\phi(1020)$. The momentum is known, and the opposite kaon is measured, to give the kaon direction. The decay kaon may be at angles of order 36 mrad, but electron momenta will be only of order 5 MeV/c, below the spectrometer minimum momentum for detection, in normal running.

(5) For the KOPIO experiment [12] BNL has proposed an intense neutral kaon beam of 0.7 GeV/c average momentum, with time-of-flight tagging allowing momentum determination of the K^0 to within a few per cent. The advantage of such momentum resolution is important for the K_L^0 beta decay. The outgoing kaon would have an angle ranging out to about 6 mrad from the incident beam, and the electron momentum would range up to about 13 MeV/c. The KOPIO experiment as proposed does not include any provision for a magnetic spectrometer (or any other charged particle identification except for identification of electrons and positrons in the electromagnetic calorimeter).

(6) Fermilab has a proposed experiment KAMI (Kaons at the Main Injector) [13] with K^0 momentum about 10 GeV/c. The momentum of this beam is too high for time of flight momentum measurement of the beam, but the proposed experiment has a charged particle spectrometer which could detect a fast outgoing charged particle close to the beam and a slow wide angle particle appropriate for the electron or positron. No charged particle identification is included at this time, beyond the comparison of energy deposit with momentum measured in the spectrometer. The kaon would be within about 0.4 mrad of the incident K^0 direction, and the electron momentum would range up to about 160 MeV/c. This experiment is essentially an upgraded continuation of the KTeV experiment, with nearly the same collaborators.

(7) In KEK, a $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ experiment E391A is in preparation [14] by experimenters from KEK, Osaka University, Saga University, and Yamagata University. It will be situated in a new K^0 beamline at the 12 GeV Proton Synchrotron. The detection system consists of an array of CeF_3 crystal calorimeters to measure the energies and positions of the two gammas from the π^0 decay, and a barrel of lead-scintillator sandwich calorimeters to eliminate backgrounds involving other particles. The average kaon momentum will be about 2 GeV/c. The momentum of the electron from the kaon beta decay would range up to about 33 MeV/c, and the outgoing charged kaon would be within about 2 mrad of the incident K^0 direction. Since neither time of flight for the kaon momentum nor charged particle identification or measurement is planned, it seems unlikely that the KEK experiment as designed will observe the kaon beta decay. Let us note that a similar experiment is envisioned [15] at the planned JHF (Japan Hadron Facility) 50 GeV high intensity proton synchrotron, which is a joint project of JAERI (Japan Atomic Energy Research Institute) and KEK [16].

In summary, the (as yet unmeasured) kaon beta decay has a predicted branching fraction of $(2.53 \pm 0.10) \times 10^{-9}$ within the MD model. Observation of the decay at this level would be a test of meson dominance. A substantial departure from this prediction would be surprising within the framework of the standard model. If the elusive $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ mode is measured, and if some thought is given beforehand to details of the experimental configuration, the measurement of the kaon beta decay branching fraction may be a useful and interesting additional result. The two experiments with the most intense neutral kaon beams are KAMI at Fermilab and KOPIO at BNL. The background from the semileptonic decay to $\pi e \nu$ is of order 10^8 times the expected signal. No planned experiment has all three possible handles: incident kaon momentum and angle information; outgoing charged decay particle spectrometer; and particle identification to identify kaons and pions in the charged decay particles. Detailed studies beyond the scope of this note would be required to establish whether either the KAMI experiment (which has a charged particle spectrometer but no decay particle identification and no time of flight for the incident momentum) or the KOPIO experiment (which has time of flight for the incident kaon momentum but no charged particle spectrometer and no charged decay product particle identification) could be successful without modification of their apparatus.

ACKNOWLEDGMENTS

We are indebted to Elliott Cheu, Bob Hsiung, Konrad Kleinknecht, Dave Kraus, Ivan Mikulec, and Mike Zeller for useful discussions. This work was supported by the U.S. Department of Energy under contract No. DOE/DE-FG02-91ER-40646 and by the Grant Agency of the Czech Republic under contract No. 202/98/0095.

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FIGURES

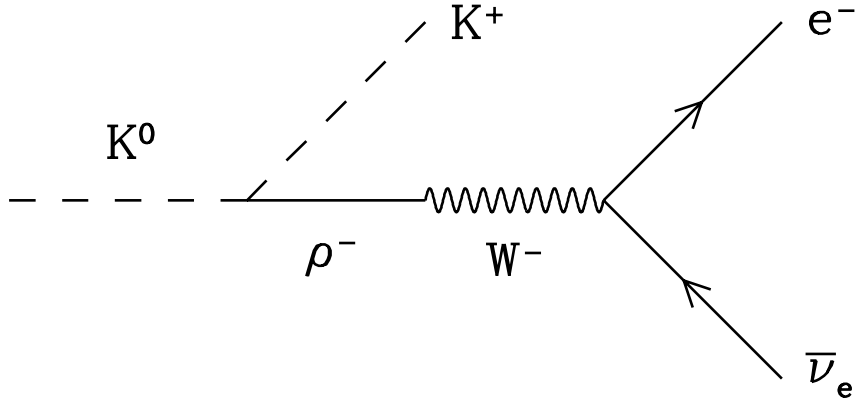


FIG. 1. Feynman diagram of the $K^0 \rightarrow K^+ e^- \bar{\nu}_e$ decay in MD approach.